# Maximum Level and Time to Peak of Dam-Break Waves on Mobile Horizontal Bed

João G. A. B. Leal[1]; Rui M. L. Ferreira[2]; and António H. Cardoso[3]

**Abstract:** This experimental study focuses the influence of bed material mobility and initial downstream water level on maximum water level and time to peak of dam-break waves. It covers horizontal bed conditions on fixed bed, sand bed, and pumice bed. Results include water surface level time evolution, maxima wave levels and time to peak. The influence of bed material mobility and downstream water level was identified and characterized, stressing the importance of using mathematical models with appropriate sediment transport formulations instead of purely hydrodynamic models to simulate dam-break waves on mobile bed channels.

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## Introduction

The most important features of dam-break flows (DBF) are the maximum wave level and time to peak. Lauber and Hager (1998) have characterized experimentally these variables for fixed, horizontal, initially dry bed downstream the dam, taking into consideration the influence of the upstream reservoir length.

Recent events and observations point out that DBF can interact strongly with the mobile bed, causing major impacts in its morphology. This was the case, for instance, downstream of Lake Ha! Ha! due to the rupture of a dyke (Lapointe et al. 1998). The occurrence of intense sediment transport in DBF as well as the interaction between the flow and the bed can significantly affect the flow dynamics, usually contributing to increase the water surface levels and to decrease the wave-front celerity as compared with purely hydrodynamic solutions (cf. Leal et al. 2006). Nevertheless, such solutions are frequently used due to difficulties in the implementation and exploitation of models accounting for the bed mobility.

The role of bed mobility in DBF was scarcely studied in the past. For lightweight granular bed material, Capart and Young (1998) observed the excavation of a scour hole near the dam cross section, leading to the onset of an hydraulic jump. Spinewine and Zech (2007) concluded that the scour hole and the hydraulic jump were significantly attenuated for heavier, less mobile bed. The effect of the water level downstream the dam was rarely studied too. Stansby et al. (1998) and Leal et al. (2002) verified that the water surface level behind the wave-front raises as compared with the pure hydrodynamic solution, creating a jump whose height increases with the initial downstream water level. The present experimental study intends to contribute to further characterize the influence of bed mobility and initial water level downstream the dam on maximum wave level and time to peak in horizontal, mobile bed channels.

[1]Assistant Professor, Dept. of Civil Engineering, Faculty of Sciences and Technology, Universidade Nova de Lisboa, Quinta da Torre, Caparica 2829-516, Portugal (corresponding author). E-mail: jleal@fct.unl.pt

[2]Assistant Professor, Dept. of Civil Engineering and Architecture, Instituto Superior Técnico, UTL, Av. Rovisco Pais, Lisbon 1049-001, Portugal. E-mail: ruif@civil.ist.utl.pt

[3]Full Professor, Dept. of Civil Engineering and Architecture, Instituto Superior Técnico, UTL, Av. Rovisco Pais, Lisbon 1049-001, Portugal. E-mail: ahc@civil.ist.utl.pt

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## Experiments

The data used in this study were collected by Leal (2005). Tests were carried out in a 19.2-m long, 0.5-m wide, and 0.7-m high rectangular flume with horizontal bed. For simulating dam-break events, a vertical lift-gate, installed in the middle cross section of the flume, was opened instantaneously. Three types of bed were adopted: fixed bed, sand bed, and pumice bed. The sand diameter was $d_s=0.8$ mm; sand specific gravity was $s=2.65$. For pumice, these variables were 1.2 mm and 1.40, respectively. The initial water depth upstream the gate was the same in all tests ($h_u=0.40$ m); for mobile bed tests, the initial bed elevation was always kept equal to 0.07 m, both up and downstream the gate; the initial water depth downstream, $h_d$, ranged from 0.000–0.210 m. The main features of the initial conditions are summarized in Table 1, where $\alpha=h_d/h_u$ is the dimensionless initial downstream water depth. Assuming hydrostatic pressure distribution, the time evolution of water surface levels was measured with seven pressure transducers installed downstream the gate, at $X=0.5$, 2.5, 5.0, 7.5, 12.5, 17.5, and 22.5, where $X=x/h_u$ and $x$=longitudinal coordinate measured from dam cross section.

## Time Evolution of Water Surface Level

Fig. 1 presents the time evolution of dimensionless water surface levels, $Z_s^*$, of fixed bed tests, $\alpha=0.00$, 0.06, 0.14, and 0.52. In Fig. 1, $Z_s^*=z_s^*/h_u$; $z_s^*$=measured water surface elevation above the initial water level downstream the gate; $T=t/(h_u/g)^{0.5}$ =dimensionless time; $t$=time; $g$=gravitational acceleration. The maxima wave levels are marked with circles; the instants of

**Table 1.** Tests Main Features

| Test | Type of bed | $h_d$ (m) | $\alpha$ (−) | Test | Type of bed | $h_d$ (m) | $\alpha$ (−) |
|---|---|---|---|---|---|---|---|
| | | | | Ts.1 | Sand $d_s$=0.8 mm $s$=2.65 | 0.003 | 0.01 |
| T.1 | fixed bed | 0.000 | 0.00 | Ts.2 | | 0.012 | 0.03 |
| T.2 | | 0.023 | 0.06 | Ts.3 | | 0.042 | 0.10 |
| T.3 | | 0.049 | 0.12 | Ts.4 | | 0.073 | 0.18 |
| T.4 | | 0.056 | 0.14 | Ts.5 | | 0.106 | 0.26 |
| T.5 | | 0.071 | 0.18 | Ts.6 | | 0.204 | 0.51 |
| T.6 | | 0.082 | 0.20 | Tp.1 | Pumice $d_s$=1.2 mm $s$=1.40 | 0.013 | 0.03 |
| T.7 | | 0.094 | 0.23 | Tp.2 | | 0.014 | 0.04 |
| T.8 | | 0.114 | 0.28 | Tp.3 | | 0.044 | 0.11 |
| T.9 | | 0.142 | 0.35 | Tp.4 | | 0.078 | 0.20 |
| T.10 | | 0.212 | 0.52 | Tp.5 | | 0.107 | 0.27 |
| | | | | Tp.6 | | 0.207 | 0.51 |

time—time limits—above which the limited upstream reservoir length starts to influence the wave levels at the measuring cross sections are also identified with vertical dashed lines. Time limits were calculated by assuming that the negative wave-front celerities measured by Leal et al. (2002) also apply downstream. For a given location, $X$, the time limit is therefore computed as $(2\lambda_r+X)/C_{NF}$, where $\lambda_r = L_r/h_u$=dimensionless reservoir length; $L_r$=length of the upstream reservoir; $C_{NF}$=dimensionless negative wave-front celerity.

For the lower values of $\alpha$ [$\alpha=0.00$, Fig. 1(a), and $\alpha=0.06$, Fig. 1(b)], the water surface level rises abruptly, in each section, immediately after the arrival of the wave-front; afterwards, it increases slowly until reaching the maximum; afterwards, the water level decreases slowly as the upstream reservoir empties. This behavior was also observed by Lauber and Hager (1998) for fixed horizontal bed. For higher values of $\alpha$ [$\alpha=0.14$, Fig. 1(c), and $\alpha=0.52$, Fig. 1(d)], water levels are influenced, after some time, by reflection waves induced by the downstream weir used to guarantee the water level downstream the gate. Whenever this occurred the "corrupted" parts of the records were ignored in the analysis. As $\alpha$ increases, the maxima wave levels are attained sooner and tend to become independent of the reservoir length, i.e., they occur before the calculated time limit. For the highest value of $\alpha$ [$\alpha=0.52$, Fig. 1(d)] the maxima wave levels are attained just after the arrival of the wave-front due to the fact that the wave propagates downstream as a solitary wave or as a group of waves (cf. Leal 2005).

For sand bed, the time evolution of the water surface elevation is practically as described above. Still, the maxima wave levels at $X=0.5$ are attained slightly sooner (cf. Leal 2005).

Fig. 2 presents the time evolution of the dimensionless water surface levels of pumice bed tests, $\alpha=0.03$, 0.11, 0.20 and 0.51. Again, the water surface behavior presents qualitative similarities with the one described for fixed bed. Important discrepancies are observed, however, at the cross section the nearest to the gate for the lower $\alpha$ values [Figs. 2(a and b)], where the water surface level does not rise slowly until reaching its maximum. Instead, it exhibits an oscillatory behavior; the maximum level is attained much sooner than for the other sections and is independent of the reservoir length. It can be concluded that, for locations near the gate, the increase of bed mobility induces the increase of the water surface levels. Although this can be attributed to the added

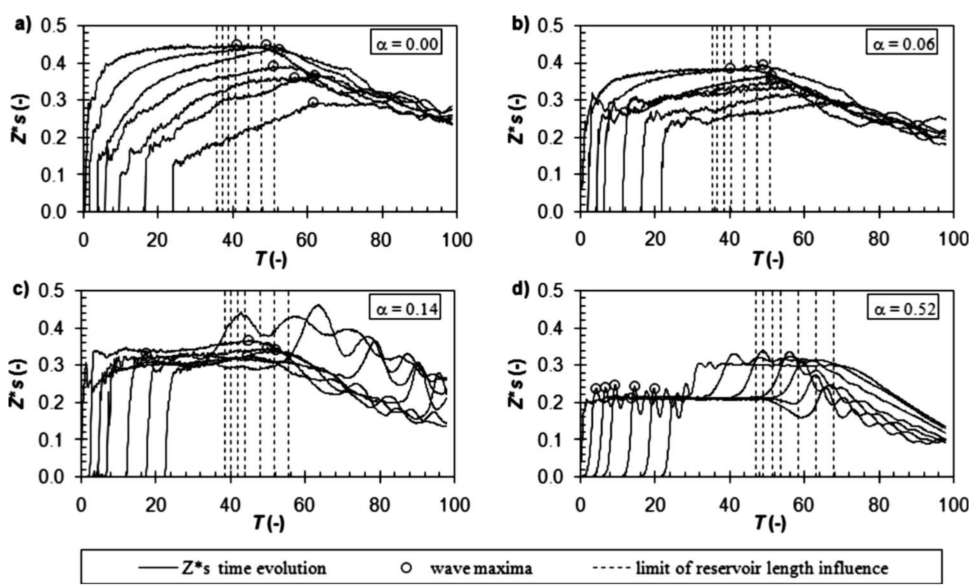


**Fig. 1.** Time evolution of dimensionless water level, $Z_s^*$, at $X$=0.5, 2.5, 5.0, 7.5, 12.5, 17.5 and 22.5 (right to left) for fixed bed tests: (a) $\alpha$=0.00; (b) $\alpha$=0.06; (c) $\alpha$=0.14; and (d) $\alpha$=0.52

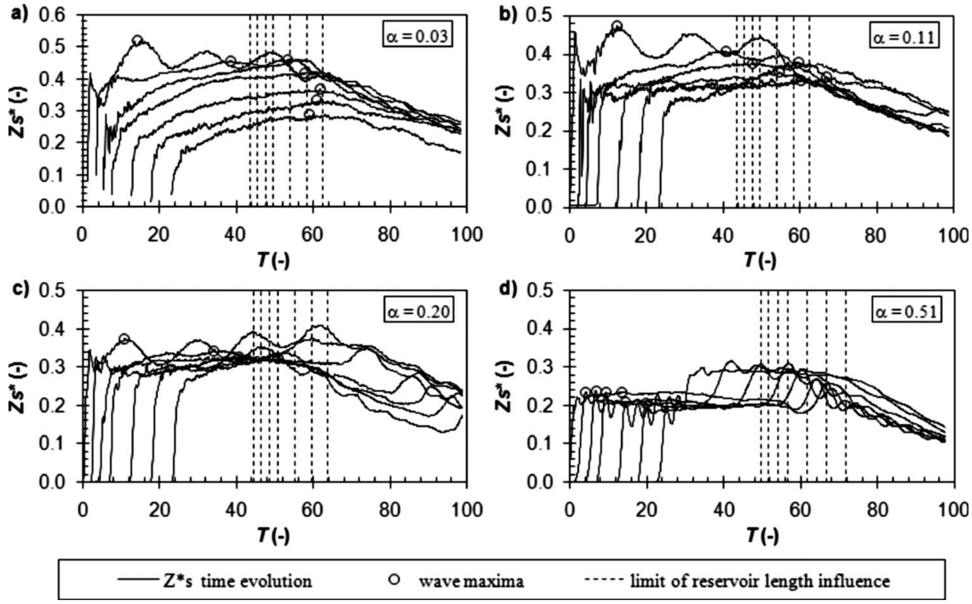


**Fig. 2.** Time evolution of dimensionless water level, $Z_s^*$, at $X$=0.5, 2.5, 5.0, 7.5, 12.5, 17.5 and 22.5 (right to left) for pumice bed tests: (a) $\alpha$ =0.03; (b) $\alpha$=0.11; (c) $\alpha$=0.20; and (d) $\alpha$=0.51

sediment inertia and to the increase of flow resistance, it should be mostly dictated by morphological changes—scour hole—observed in the bed profile (cf. Leal 2005).

## Maxima Wave Levels

It was found that maxima wave levels, $(Z_s^*)_{\max}$, can be fitted by the following relation

$$1/(Z_s^*)_{\max} = (a_1\alpha + a_3)X + (a_2\alpha + a_4) \quad (1)$$

where $a_1$, $a_2$, $a_3$ and $a_4$=regressions coefficients which depend on the bed type, according to Table 2. Fig. 3 plots Eq. (1) against the experimental data. The equation proposed by Lauber and Hager (1998) for fixed, horizontal dry bed

$$(Z_s^*)_{\max} = \frac{4}{9}\left(1 + \frac{1}{X^*}\right)^{-5/4} \quad (2)$$

where $X^* = \lambda_r X^{-2/3}$, is also included in Fig. 3(a). For fixed and sand bed tests, $\alpha < \approx 0.2$, as well as for pumice bed tests, $\alpha < \approx 0.3$, $1/(Z_s^*)_{\max}$ increases linearly with $X$, i.e., the maximum water surface elevation decreases with $X$. This can be attributed to the finite length of the reservoir and is in accordance with reported real cases. However, for higher values of $\alpha$, waves behave as solitary waves or groups of waves, the kinetic energy converts into potential energy through the increase of the water surface elevation and the influence of the upstream reservoir length ultimately ceases. The influence of the initial downstream water level (i.e., $\alpha$) decays with $X$, since, for high $X$ values, maxima water

**Table 2.** Regression Coefficients of Eq. (1)

| Type of bed | $a_1$ (−) | $a_2$ (−) | $a_3$ (−) | $a_4$ (−) |
|---|---|---|---|---|
| Fixed | −0.2233 | 4.3681 | 0.0431 | 2.2354 |
| Sand | −0.2598 | 4.4543 | 0.0630 | 2.0880 |
| Pumice | −0.1894 | 5.1618 | 0.0744 | 1.7340 |

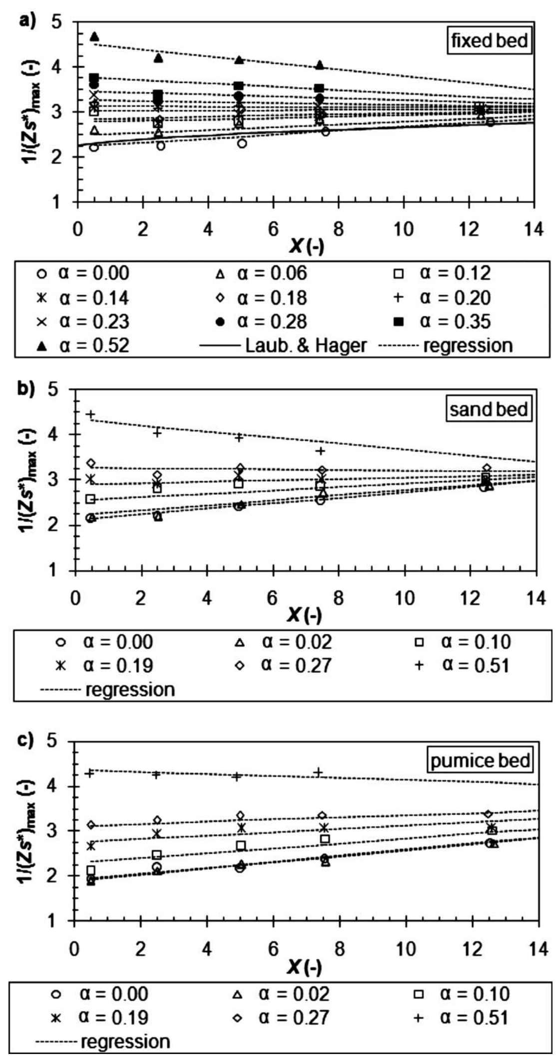


**Fig. 3.** Variation of dimensionless maximum wave level, $1/(Z_s^*)_{\max}$, with $X$ for: (a) fixed bed; (b) sand bed; and (c) pumice bed

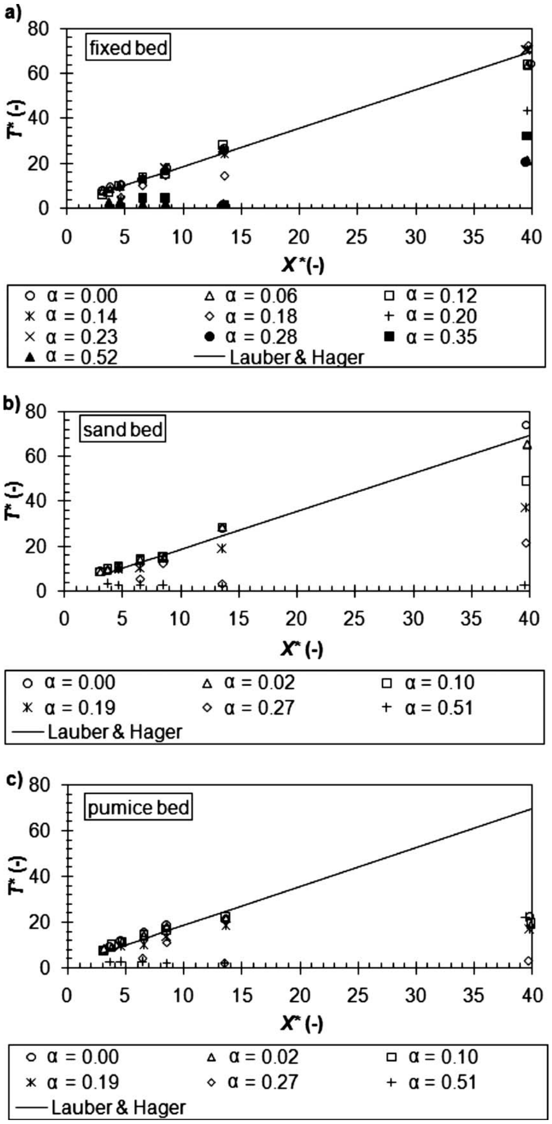


**Fig. 4.** Variation of dimensionless time to peak, $T^*$, with $X^*$: (a) fixed bed; (b) sand bed; and (c) pumice bed

surface levels tend to a constant value irrespective of $\alpha$.

Although the described behavior applies to the three bed types, pumice bed results are somewhat different from fixed bed and sand bed. For small values of $\alpha$, the water surface level is slightly higher, which is in accordance to what was mentioned before, i.e., the bed morphological changes and the flow-bed interaction increase the maxima wave levels, especially near the gate cross section.

## Time to Peak

Fig. 4 presents the variation of the dimensionless time to peak, $T^*=T_{\max}X^{-2/3}$, with $X$. $T_{\max}=t_{\max}(g/h_u)^{1/2}$; $t_{\max}$=time to peak, associated to the maximum water level. The equation proposed by Lauber and Hager (1998) for fixed, horizontal dry bed is also plotted

$$T^* = 1.7(1+X^*) \tag{3}$$

From Fig. 4, it can be concluded that the equation of Lauber and Hager (1998) is a rather good predictor as soon as $\alpha < \approx 0.14$ and $X^* < 15$. Since higher values of $X^*$ correspond to cross sections located near the gate, it can also be concluded that the morphological changes occurring in the mobile bed influence mostly the time to peak at those sections. For high $\alpha$ values, the wave maxima levels are attained shortly after the wave-front arrival. Nevertheless, the influence of the water depth downstream (i.e., $\alpha$) on time to peak is smaller as $X^*$ decreases.

## Conclusions

From the previous sections and within the range of covered experimental conditions, the following conclusions can be drawn: (1) maxima wave levels near the gate are higher and attained sooner for highly movable bed material (pumice) as compared with fixed bed, and become independent of the upstream reservoir length; (2) for small initial water depth downstream the gate, the maxima wave levels decrease in the downstream direction, while the opposite trend is observed for high initial water depth; (3) the influence of the water depth downstream—expressed by $\alpha$—on the amplitude of water level variations and on time to peak is attenuated in the downstream direction.

These results stress the importance of using mathematical models incorporating appropriate sediment transport formulations instead of purely hydrodynamic models to propagate dam-break waves on mobile bed channels.

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## Notation

*The following symbols are used in this technical note:*

$a_1, a_2, a_3, a_4$ = regressions coefficients of Eq. (1);
$C_{NF}$ = dimensionless celerity of the negative wave-front;
$d_s$ = sediment mean diameter;
$g$ = gravitational acceleration;
$h$ = flow depth;
$h_d$ = initial water depth downstream;
$h_u$ = initial water depth upstream;
$L_r$ = upstream reservoir length;
$s$ = sediment specific gravity;
$T$ = dimensionless time after the dam-break;
$T^*$ = dimensionless time to peak defined as $T_{\max}X^{-2/3}$;
$T_{\max}$ = dimensionless time to peak;
$t$ = time after the dam-break;
$t_{\max}$ = time to peak;
$X$ = dimensionless location from the dam;
$X^*$ = dimensionless length parameter defined as $\lambda_r X^{-2/3}$;
$x$ = location from the dam section;
$Z_s^*$ = dimensionless water surface elevation measured from the initial water level downstream of the dam;
$z_s^*$ = water surface elevation measured from the initial water level downstream of the dam;

$\alpha$ = dimensionless initial downstream water depth; and

$\lambda_r$ = dimensionless upstream reservoir length.

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